The effect of static magnetic field on heart rate variability – an experimental study

T. Koppel[1,*], I. Vilcane[2], M. Carlberg[3], P. Tint[1], R. Priiman[4], K. Riisik,
H. Haldre[4] and L. Visnapuu

[1]Tallinn University of Technology, Department of Work Environment and Safety, Ehitajate tee 5, EE19086 Tallinn, Estonia; *Correspondence: tarmo.koppel@ttu.ee
[2]Riga Technical University, Institute of Occupational Safety and Civil Defence, Kalnciema Street 6, LV-1048 Riga, Latvia
[3]Department of Oncology, Faculty of Medicine and Health, Örebro University, SE-701 82 Örebro, Sweden
[4]Institute of Environmental Health and Safety

Abstract. The aim of this study was to investigate the effect of weak static magnetic fields on human heart rate variability (HRV). So far, literature has mainly focused on the health effects induced by strong static magnetic fields. HRV is a temporal fluctuation of heart rate, which the literature has shown to be an adequate indicator for assessing the state of the autonomic nervous system. By autonomic nervous system one could also assess in real time if and when the organism falls into stress. In this blind experiment the subjects were exposed to 150 microTesla magnetic field for a few minutes. The heart activity of the subjects *(n* = 116) was recorded and the dynamics of the HRV frequency components i.e. reaction of the sympathetic and parasympathetic nervous system analyzed by repeated measures analysis of variance (ANOVA). No statistically significant difference ($p < 0.05$) were found in low frequency (LF), high frequency (HF), total power (TP), HF/TP ratio, LF/HF ratio nor between hear rate (HR) means in between the exposure and pre- or post-control stages of the experiment. However, observations made by the researchers suggest, that a small portion of the population may indeed be affected by slightly elevated static magnetic fields but the screening method needs further elaboration.

Key words: static magnetic field, heart rate variability, HRV, autonomic nervous system.

INTRODUCTION

Scientific literature is scarce in regard to studies on weak static magnetic fields effects on humans. The literature has mainly focused on strong magnetic fields, such as present in industrial processes like electrolysis, aluminum production and other activities which consume a lot of electrical current. Also, strong static magnetic fields can be encountered close to magnetic resonance tomography (MRT) devices and some other medical therapy devices. Close to such instruments the magnetic field may vary extend from hundreds of milliTeslas to few Teslas. In comparison, the natural magnetic field in Estonia is about 51 microTeslas (μT). The public safety limit for static magnetic fields in Estonia is 40 milliTeslas (mT) (MS, 2002). Based on the new European directive (2013/35/EU) the maximum allowed occupational exposure is even higher: 2 or 8

Teslas (T) depending on whether the environment is controlled or not (EP, 2013). The afore mentioned safety limits are set to prevent well known sensory or health effects induced by the static magnetic field. The field strength applied in this study is several orders of magnitude lower than legal safety limits. Such low field strengths may also be encountered near larger ferromagnetic objects, e.g. construction supporting structures where a lot of iron is applied.

HRV is an expression of a heart rate variation in time in between consecutives heartbeats (R-R interval). The recorded R-R intervals compose a rythmogram that is subjected to a time domain analysis (mean and standard deviation of heart rate) and frequency domain analysis (power in the low and high frequency spans and total spectral power TP over all of these spans).

In recent times HRV has found more use as both diagnostic tool and therapeutic guide in the field of medicine. HRV has been confirmed as a diagnosis tool for the state of the autonomic nervous system (Malik et al., 1996; Melillo et al 2011) and as a predictor of survival in heart failure cases (Ho et al., 1997).

Chronic heart failure is associated with autonomic dysfunction, that can be quantified by measuring HRV. A reduction in standard deviation of all normal RR intervals (SDNN) identifies patients at high risk of death and is a better predictor of death due to progressive heart failure than other conventional clinical measurements (Nolan et al., 1998).

Altered HRV and heart rate dynamics have found to have prognostic significance for the progression of coronary artery disease and mortality after certain heart conditions (Jokinen, 2003). HRV biofeedback has been successfully used to decrease major depressive disorder (Karavidas, 2008).

HRV has been utilized only by some researchers to investigate the effects from the electromagnetic fields. Andrzejak et al. (2008) exposed 32 students to a radiofrequency electromagnetic field from a mobile phone call (20min) and found an increase in parasympathetic tone while sympathetic tone was reduced: low frequency (LF) / high frequency (HF) ratio got lower during the call (Andrzejak et al., 2008).

Parazzini et al. exposed subjects to a full power (2W) of a GSM mobile phone and concluded that there were no statistical significant effect on the main (R-R mean) and most of the rest HRV parameters due to the EMF exposure. However, a weak interaction between some HRV parameters (SDNN, TINN, and triangular index in time domain and LF power in frequency domain analysis) and RF exposure was observed (Parazzini et al., 2007). The group's later analysis using nonlinear dynamics of HRV on the same data set, also showed no statistically significant effect due to GSM exposure (Parazzini et al., 2013).

Wilén et al. (2007) investigated HRV of the radiofrequency (RF) plastic sealer operators ($n = 35$) and found a significantly increased total power (TP) and very low frequency (VLF) power during nightshift amongst RF operators as compared to the control group. The RF sealer operators exhibited relative increase in parasympathetic cardiac modulation, which the authors hypothesized to be a result of chronic low level RF exposure on the thermoregulatory mechanism of the body, rather than from the non-thermal mechanism on the cardiovascular system (Wilén et al., 2007).

A study by Bortkiewicz et al. (2006) concluded that worker exposed to elevated levels of 50 Hz electromagnetic fields influences neurovegetative regulation of the cardiovascular system: the relative risk of decreased HRV was significantly higher in

the exposed group as compared to the control (OR = 2.8). According to their findings, VLF exhibit significantly more power in the exposed group and even correlate with the exposure; also, in the exposed group there were more people with dominant sympathetic function (LF/HF>1) (65%) than in controls (47%) (Bortkiewicz et al., 2006).

All consumer electronics must comply with legally set safety limits, which 1) in case of radiofrequency fields are set to prevent health effects from heating of the tissues, 2) to prevent electric stimulation of peripheral and central nervous system tissues (1Hz-10MHz) and 3) to prevent vertigo and other physiological effects related to disturbance of the human balance organ resulting from moving in a static magnetic field (ICNIRP 1998; CEC 1989 & 1999; EP 2013). The scientific literature has also suggested other health effects, e.g. Bioinitiative report (2010; 2012), but these are yet not well accepted/confirmed by the whole scientific community, as the underlying mechanism is often unclear and the experiments are not always repeatable (Bioinitiative, 2010 & 2012; EHFHRAN, 2010).

The literature does not however provide studies done involving HRV-analysis and weak static magnetic fields from the point of view of this study. However, there exists a niche of research of fluctuations in the natural magnetic field of the Earth and their induced health effects. Some of these studies have investigated HRV during magnetic storms. Cornélissen et al. (2002) in their review article concluded magnetic field fluctuations to decrease heart rate variability. Such magnetic storm events were seen mostly to decrease spectral power of VLF (< 0.04Hz) and LF band (0.04–0.15Hz) and no influence on HF band (0.15–0.40Hz) (Cornélissen et al., 2002; Chibisov et al., 1995; Otsuka(ed.) Proceedings, 2000).

This study was conducted to investigate the effect of weak static magnetic fields on human heart rate variability (HRV).

MATERIALS AND METHODS

The current study is about exposing the subject to a weak static magnetic field and analyzing the dynamics of heart rate variability. The nominal field strength at the center of the subject's head is ~150 µT which in case of static magnetic fields may be classified as very weak.

The subjects of the study are voluntaries in different ages. The measurements were conducted in the companies and other types of organizations and facilities, where the members of that organization were invited to participate in the study. People under heart medication were excluded from the sample. Also, people who reported their health being weak or sick were also excluded from the sample. The test was performed individually with each subject. The subject was placed in a private space separated from the test operators. The subject had no view on what the operators were doing. In selecting the sitting place for the subject, it was sought that all the emotional stimuli would be minimized in the room.

Other environmental electromagnetic field parameters were also checked prior to the test: 1) low and intermediate frequency electric field, 2) low and intermediate frequency magnetic field and 3) radiofrequency electromagnetic field. Also the electromagnetic emissions from the research instruments were under the control. All electronics devices were removed from the measurement area (including mobile

phones). By measuring the afore-mentioned components of the electromagnetic field almost the entire spectrum of the EMFs were taken under the control.

In order to exclude other external factors influencing the test, attention was paid also to other environmental factors. A national standard EVS-EN 15251:2007 was used as a guideline for controlling lighting, noise, indoor air quality (excluding the exchange of air) and temperature (ES, 2007).

The research instrumentation consisted of 1) equipment used for magnetic field generation and 2) heart rate measurement instruments. Static magnetic field was generated using an electromagnetic air-core coil, distanced 0.3 m from the center of the head (Fig. 1).
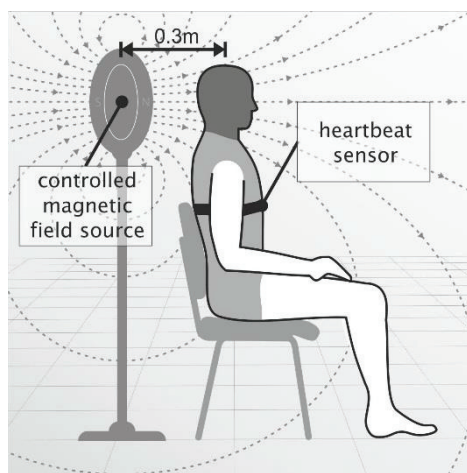

Figure 1. The placement of the subject and the magnetic field source.

The set nominal magnetic field (150 µT at the center of the head) was checked by magnetometric measurements. Measurements were conducted using a fluxgate triple axis magnetometer Walker Scientific FGM-5DTAA. Voltage dynamics at the electromagnetic coil's terminals were checked with a 60 MHz oscilloscope (Hantek DSO-2150).

By moving from the center of the head towards the electromagnetic coil, the magnetic field also increases, therefore the backside of the head was exposed to somewhat higher magnetic field (~200 µT). The diameter of the electromagnetic coil was 0.4m which guaranteed wide exposure to the whole head region. The magnetic field was switched on by the operator from a distance, using a specialized control unit.

Heart rate variability was registered and analysis on the autonomic nervous system reaction was performed in real-time with a non-invasive hard- and software system Nerve-Express 2.4 (Heart Rhythm Instruments, Inc. NY USA). The system registers subject's each heartbeat (R-R interval) and distributes these into 192-beat episodes. The reaction to the intervention is determined by calculating the heart rate variability during the selected episode (a period of 192 heartbeats). Frequency domain measures were applied to calculate the power in the bands of 0.033–0.07 Hz (low frequency-LF2), 0.07–0.15 Hz (low frequency-LF1), 0.033–0.15 Hz (LF+LF2), 0.15–0.5 Hz (high

frequency-HF) and total spectral power (TP) over all three bands (0.033–0.5 Hz). The analysis mainly focuses on the HF band.

The dynamic behavior of the nervous system is used to assess the effect the magnetic field has on the individual.

The heartrate is registered using a heartrate monitor chest strap sensor, that forwards the signal to the hardware receiver by a 5.3 kHz radio signal, which is connected to a laptop personal computer (Fig. 2).
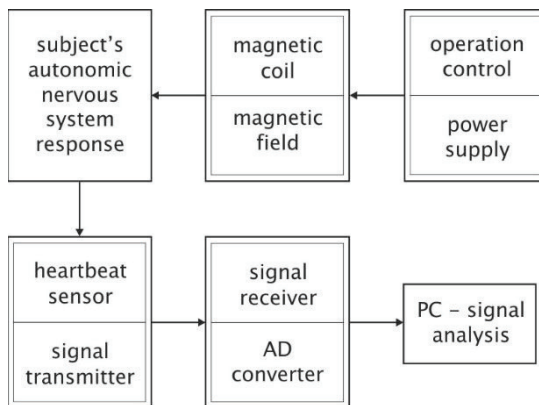

Figure 2. The setup of the research instrumentation and the context of collecting the data.

The subjects were asked to sit in a comfortable position and to refrain oneself from sudden or larger physiological movements, since these may alter the behavior of the heartrate variability. In order to exclude the effect on cardiovascular activity from changing the posture (from walking/standing to sitting), it was also required that prior to testing the subject would have been in a sitting position for a sufficient time.

The subjects were also instructed to avoid any emotional burden during the test – this meant avoiding any negative or positive emotional thoughts. In turn the subjects were asked to watch outside of the window (at the trees and landscape) or at the corresponding picture on the wall or the nature video on the computer screen. During the test the room was kept quiet and nobody was allowed to address the subject.

The operator activated the magnetic field by a remote unit. Nominal magnetic field was established and dropped smoothly: 100% magnetic field was deployed in 0.15 sec from switching and it dissipated in 1 sec after switch-off.

Blind experiment criteria were followed in setting up the test. The measurement period was divided into episodes of 192 heartbeats, consequently each episode took about 2–3 min, depending on the heart rate. During the test there was one exposure episode and several control episodes. The subject was not informed when the exposure to the magnetic field would take place, neither when one or another episode would start or end. The turn of the exposure episode was selected randomly, given that previously there had been at least two control episodes. The operator also sought that prior to the exposure episode the nervous system would exhibit stability in two pre-control episodes. This procedural requirement would minimize the possibility of false positives from variations in cardiovascular activity.

The values for pre-control (the stage right before the exposure), exposure and post-control stages were compared using repeated-measures ANOVA with Huynh–Feldt correction followed by linear contrasts for pairwise comparisons. All variables except HF/TP were log-transformed prior to analyses to normalize the distributions. For HF/TP square-root transformation was used. The statistical level of significance was set to $p = 0.05$. The statistical analyses were done using StataSE 12.1 (Stata/SE 12.1 for Windows; StataCorp, College Station, TX).

RESULTS AND DISCUSSION

The measurements were performed in Estonia and Latvia.

The sample ($n = 116$) consisted of 84 females and 32 males. The youngest person was 20 and the oldest 83 years of age. The age distribution of the sample is following:

20–34y – 40 persons; 35–49y – 41 persons; 50–64y – 25 persons; 65+y – 10 persons.

A repeated measures analysis of variance (ANOVA) with Huynh-Feldt correction was done to assess if there is change in subjects' HRV indicators when measured before (i.e. pre-control episode, right before the exposure), during (exposure episode) and after (post-control episode) the exposure to the magnetic field. The results of the ANOVA show no statistically significant effect ($p < 0.05$), as shown in Table 1 (results from linear contrasts i.e. pairwise comparisons, are shown as p-values; the values for HF, TP, LF/HF, LF1, LF2 and HR were log-transformed and the values for HF/TP were square-root transformed prior to analysis). Thus, there is no statistically significant evidence in temporal differences for HF, TP, LF/HF, LF1, LF2, HR and HF/TP ratio. Also, each pairwise comparison proved neither to be statistically significant ($p < 0.05$).

Table 1. Tests of differences between pre-control, exposure and post-control for HF (ms²), TP (ms²), LF1 (ms²), LF2 (ms²), HR (bpm), HF/TP ratio (n = 116)

	HF	TP	LF/HF	LF1	LF2	HR	HF/TP
Repeated-measures ANOVA overall comparisons							
Pre-control ($\bar{x}$)	3,188.5	7,529.9	3.77	2,118.4	2,072.4	75.6	0.347
Exposure ($\bar{x}$)	3,164.4	7,671.2	3.87	2,310.3	2,041.6	75.4	0.352
Post-control ($\bar{x}$)	3,392.4	8,604.5	6.32	2,761.2	2,306.5	75.4	0.329
p-value	0.58	0.79	0.19	0.25	0.22	0.62	0.16
Linear contrasts							
Pre-control vs exposure (*p*)	0.98	0.80	0.74	0.35	0.12	0.41	0.66
Pre-control vs post-control (*p*)	0.37	0.67	0.17	0.09	0.92	0.39	0.16
Exposure vs post-control (*p*)	0.38	0.50	0.09	0.46	0.15	0.97	0.06

$\bar{x}$ = mean; p = p–value

However, the observations made by the researchers indicate that the effect of the magnetic field might still be real for some individuals, which would require a larger sample size and more detailed statistics to show with statistical significance. While monitoring individual tests in real-time (*Nerve–Express* software), the researchers found, the autonomic nervous system balance fluctuation to correlate with the exposure to the magnetic field in a number of cases. Some individuals seemed to react to the

magnetic field with a decrease in the spectral components power (LF n = 2; HF n = 9) while others showed increase (LF n = 5; HF n = 16).

Next, a measurement of a 20y old man is presented, representing an individual with suspected reaction to the elevated static magnetic field (Figs 3–4). It is a typical case, where pre- and post-control stages differ from the exposure stage (3rd). Subject's heart rate variability decreased at the 3rd stage when the exposure to the magnetic field took place. Fig. 3 shows weaker variability amplitude at the 3rd stage of the rythmogram, whereas at the 4th stage (no magnetic field) the variability recovered. Fig. 4 indicates weaker power at the frequency span of 0.04–0.15 Hz (LF); total of four stages are pictured, episodes 1, 2 and 4 were without magnetic field.
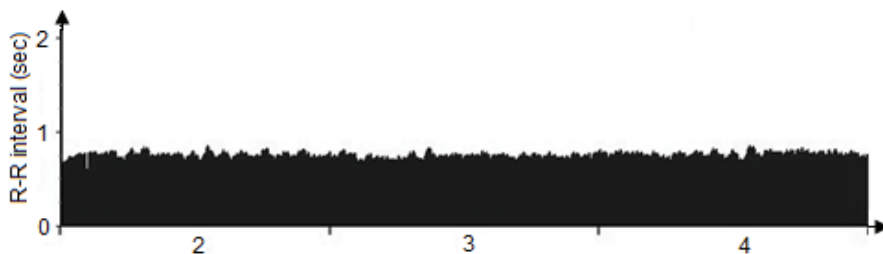

Figure 3. Heart rate rythmogram of a twenty year old male subject whose heart rate variability decreased at the 3rd episode (exposure); vertical axis – R-R interval (sec); horizontal axis – episodes (each episode consists of 192 heartbeats).
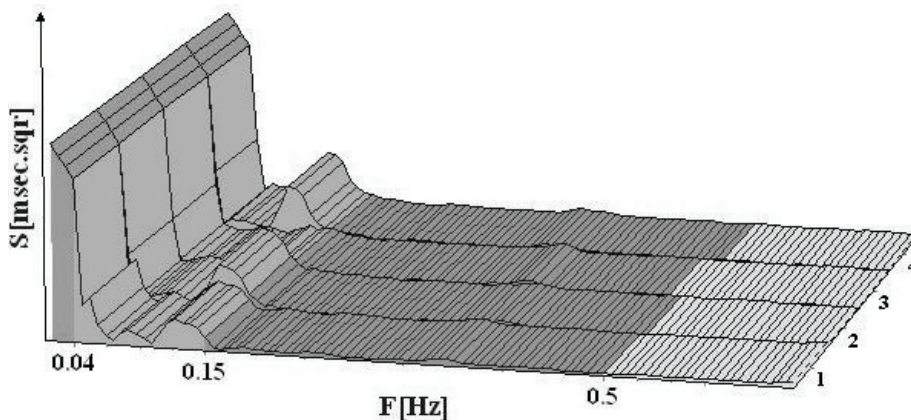

Figure 4. Spectral function of a twenty year old male subject; exposure at the 3rd stage; vertical axis – relative amplitude of spectral harmonics (S, msec²); horizontal axis – frequencies (Hz).

The literature does not however provide much studies like this one. HRV decrease discussed by Cornélissen et al. (2002), Chibisov et al. (1995), Otsuka(ed.), (2000). Proceedings, 2000 are related to the fluctuations in the static magnetic field of the Earth, which in essence are time-varying and not static.

The authors suggest follow-up studies, to utilize questionnaires to find out what personal traits and health characteristics may explain the change in the HRV due to the

exposure to the static magnetic field. Such questionnaire would also investigate subjects' exposure to other electromagnetic fields in a daily life.

Future research should encompass more subjects, to have a reliable assessment on how much of the population are affected by the elevated magnetic field. Attention should also be paid on testing the same individual on more than one occasion – to find out if the reaction occurs also on other day or time of day.

Considering the short length of the exposure, it is also worth investigating if longer exposure to the same field strength would result in reaction in more people. Follow-up studies should also clarify, why some people exhibit reaction and others not. The cofounding factor may be the general status of health, sporting habits, diet and environmental sensitivity to other risk factors (e.g. noise). It is also worth investigating, if those that reacted to the elevated static magnetic field would also react to other parts of the electromagnetic spectrum: 1) low frequency, 2) intermediate frequency and 3) radiofrequency electric, magnetic and electromagnetic fields.

CONCLUSIONS

This study has suggested that some people may exhibit change in the heart rate variability as a reaction to weak static magnetic fields. However the results are not statistically significant. The finding may be considered worth of further investigations since 1) the used field strength resides below the legal safety limit and 2) the exposure was short term ($\sim$2½ min).

Since the magnetic field source was positioned close to the subject, one must also consider that the field was not homogeneous. Therefore the affecting factor may not only be the elevated magnetic field itself, but also the abrupt gradient of the field. However sudden head movements can be excluded as a causing factor, since subjects were well instructed to move only slowly, if at all.

It's possible that we are dealing with an individual sensitivity – some members of the public may react to the magnetic field, whereas others don't. Atlasz et al. (2006) exposed their sample to the radiofrequency electromagnetic field and noticed that 9% of the subjects had alterations in their HRV after the exposure, though their sample size was small ($n = 35$).

REFERENCES

Andrzejak, R., Poreba R, Poreba, M., Derkacz, A., Skalik, R., Gac, P., Beck, B., Steinmetz-Beck, A., Pilecki, W. 2008. The influence of the call with a mobile phone on heart rate variability parameters in healthy volunteers. *Industrial Health* **46,** 409–417.

Atlasz, T., Kellényi, L., Kovács, P., Babai, N., Thuróczy, G., Hejjel, L., Hernádi, I. 2006. The application of surface plethysmography for heart rate variability analysis after GSM radiofrequency exposure. *J. Biochem. Biophys. Methods* **69,** 233–236.

BioInitiative Working Group 2007. Bioinitiative report: A Rationale for a Biologically Based Public Exposure Standard for Electromagnetic Fields.

BioInitiative Working Group, Sage, C. & Carpenter, D.O. (Editors). 2012. BioInitiative Report: A Rationale for a Biologically-based Public Exposure Standard for Electromagnetic Radiation. *http:// www.bioinitiative.org*. Accessed 31.12.2012.

Bortkiewicz, A., Gadzicka, E., Zmyślony, M., Szymczak, W. 2006. Neurovegetative disturbances in workers exposed to 50 Hz electromagnetic fields. *International Journal of Occupational Medicine and Environmental Health* **19**(1), 53–60.

CEC-Council of the European Communities. Council Directive 89/336/EEC of 3 May 1989 on the approximation of the laws of the Member States relating to electromagnetic compatibility (89/336/EEC), Official Journal L 139, 23/05/1989 P. 0019–0026.

CEC–Council of the European Communities. Recommendation of the Council 1999/519/EC on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). *Official Journal of the European Communities*, 30. 7. 1999.

Chibisov, S.M., Breus, T.K., Levitin, A.E., Drogova, G.M. 1995. Biological effects of planetary magnetic storms. *Biofizika* **40**, 959–968.

Cornélissen, G., Halberg, F., Breus, T., Syutkina, E.V., Baevsky, R., Weydahl, A., Watanabe, Y., Otsuka, K., Siegelova, J., Fiser, B., Bakken, E.E. 2002. Non-photic solar associations of heart rate variability and myocardial infarction. *Journal of Atmospheric and Solar-Terrestrial Physics* **64**(5–6), 707–720.

EHFHRAN–European Health Risk Assessment Network on Electromagnetic Fields Exposure 2010. Risk Analysis of human exposure to electromagnetic fields, report D2 of EHFRAN project. *http://efhran.polimi.it/docs/EFHRAN_D2_final.pdf*. Accessed 6.12.2014.

EP-European Parliament. Directive 2013/35/EU of the European Parliament and the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) and repealing Directive 2004/40/EC. *Official Journal of the European Union* 29.6.2013.

ES-Estonian Standards Center. Estonian Standard EVS-EN 15251:2007 Source data for planning and assessing the energy efficiency of the buildings based on the quality of the indoor air, thermal comfort, lighting and acoustics. Inure July 2007 (in Estonian).

Heart Rhythm Instruments Inc. 2002. Nerve-Express System Guide & User's Manual, NJ USA.

Ho, K.K., Moody, G.B., Peng, C.K., Mietus, J.E., Larson, M.G., Levy, D., Goldberger, A.L. 1998. Predicting survival in heart failure case and control subjects by use of fully automated methods for deriving nonlinear and conventional indices of heart rate dynamics. *Circulation.* **96**(3), 842.

ICNIRP-International Commission of Non-Ionising Radiation Protection 1998. Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields. *http://www.icnirp.de/documents/emfgdl.pdf*. Accessed 1.12.2014.

Jokinen, V. 2003. Longitudinal changes and prognostic significance of cardiovascular autonomic regulation assessed by heart rate variability and analysis of non-linear heart rate dynamics. Department of Internal Medicine, University of Oulu.

Kravidas, M. 2008. Heart rate variability biofeedback for major depression. *Biofeedback* **36**(1), 18–21.

Malik, M., Bigger, J.T., Camm, A.J., Kleiger, R.E., Malliani, A., Moss, A.J., Schwartz, P.J. 1996. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Eur Heart J* **17**, 354–381.

Melillo, P., Bracale, M., Pecchia, L. 2011. Nonlinear Heart Rate Variability features for real-life stress detection. Case study: students under stress due to university examination. *BioMedical Engineering OnLine* **10**, 96.

Nolan, J., Batin, P.D., Andrews, R., Lindsay, S.J., Brooksby, P., Mullen, M., Baig, W., Flapan, A.D., Cowley, A., Prescott, R.J., Neilson, J.M., Fox, K.A. 1998. Prospective study of heart rate variability and mortality in chronic heart failure: results of the United Kingdom heart failure evaluation and assessment of risk trial (UK-heart). *Circulation* **15**, 1510.

Otsuka, K. (ed.). 2000. *Proceedings, First International Symposium, Workshop on Chronoastrobiology & Chronotherapy (Satellite Symposium, Seventh Annual Meeting, Japanese Society for Chronobiology)*. Kudan, Chiyodaku, Tokyo, 11.11.2000.

Parazzini, M., Ravazzani, P., Tognola, G., Thuroczy, G., Molnar, F.B., Sacchettini, A., Ardesi, G., Mainardi, L.T. 2007. Electromagnetic Fields Produced by GSM Cellular Phones and Heart RateVariability. *Bioelectromagnetics* **28**, 122–129.

Parazzini, M., Ravazzani, P., Thuroczy, G., Tognola, G., Molnar, F.B., Ardesi, G., Sacchettini, A., Mainardi, L.T. 2013. Nonlinear heart rate variability measures under electromagnetic fields produced by GSM cellular phones. *Electromagnetic Biology and Medicine* **32**(2), 173–181.

SM-Regulation by the Minister of Social affairs. Limit values for non-ionizing radiation in living and recreational spaces, learning environments and measurement of the levels of non-ionizing radiation. RTL 2002, 40, 563, 21.02.2002 nr 38 (in Estonian).

VV-Regulation by the Government of the Republic. Safety limit values for physical risk factors in the work environment and the order of measurement of the prameters of risk factors, 25.01.2002 nr 54, RT I 2002, 15, 83 (in Estonian).

Wilén, J., Wiklund, U., Hörnsten, R., Sandström, M. 2007. Changes in heart rate variability among RF plastic sealer operators. *Bioelectromagnetics* **28,** 76–79.